REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*: 29-12-2005

2. REPORT TYPE: Final

3. DATES COVERED *(From - To)*: 01-11-1995 to 31-10-2005

4. TITLE AND SUBTITLE

Ocean Mixing

5a. CONTRACT NUMBER

5b. GRANT NUMBER: N00014-96-1-0250

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)

James N. Moum

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

State of Oregon acting by and thru the State Board of Higher Education
on behalf of Oregon State University
Kerr Administration Bldg, 15th and Jefferson
Corvallis, OR 97331

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research Code 322PO
Ballston Center Tower One
800 N. Quincy St.
Arlington, VA 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S): ONR 322PO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The work done under this grant falls under six broad categories, all linked by the common theme of understanding the role small-scale fluid dynamics in the ocean plays in creating turbulence and mixing and thereby influencing the larger scale oceanic flows. This grant funded a series of short experiments over Oregon's continental shelf. The six broad categories include the analysis and theoretical developments that have ensued as well as engineering technical development in aid of seagoing observations.

15. SUBJECT TERMS

ocean turbulence, microstructure, mixing, internal waves, instrument development, small-scale fluid dynamics

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	5	James N. Moum
					19b. TELEPHONE NUMBER *(Include area code)* 541-737-2553

Final Report
Moum

grant number: N00014-96-1-0250
grant period: 01-11-1995 to 31-10-2005

Ocean Mixing

James N. Moum

College of Oceanic & Atmospheric Sciences
Oregon State University
Corvallis, OR 97331-5503
ph: (541) 737-2553 fx: (541) 737-2064 email: moum@coas.oregonstate.edu
http://mixing.coas.oregonstate.edu/

The work done under this grant falls under six broad categories, all linked by the common theme of understanding the role small-scale fluid dynamics in the ocean plays in creating turbulence and mixing and thereby influencing the larger scale oceanic flows. This grant funded a series of short experiments over Oregon's continental shelf. The six broad categories include the analysis and theoretical developments that have ensued as well as engineering technical development in aid of seagoing observations.

Eddy-correlation flux measurements

A final analysis of the efficacy of eddy-correlation flux measurements was made. This followed from technical developments in the PI's previous grant that led to the construction of a new sensor capable of sensing small-scale velocity fluctuations in the flow direction.

Efficiency of mixing in the main thermocline, *J. Geophys. Res.*, **101**, 12,057–12,069, 1996. (J.N. Moum)

Energy-containing scales of turbulence in the ocean thermocline, *J. Geophys. Res.*, **101**, 14,095–14,109, 1996. (J.N. Moum)

Quantifying vertical fluxes from turbulence in the ocean, *Oceanography*, **10**, 111–115, 1998. (J.N. Moum)

Combined observational/modeling efforts

The development and maturation of a symbiotic relationship with small-scale turbulence modeling efforts (Direct Numerical Simulations – DNS and Large Eddy Simulations - LES) resulted in a new way to broaden our understanding of small-scale observations. This was primarily a collaboration with Bill Smyth (OSU). Using these, we have been able to not only enhance our understanding of our inevitably incomplete observations but also redefine observational objectives. It has led to a renewed appreciation that neither observations nor modeling is complete in itself. In each of the papers listed below, the modeling effort was driven by our detailed small-scale observations which were used as guidelines for model verification.

Turbulent dissipation during a westerly wind burst: a comparison of large eddy simulation results and microstructure measurements. *J. Phys. Oceanogr.*, **29**, 1, 1–28, 1999. (E. Skyllingstad, W.D. Smyth, J.N. Moum and H. Wijesekera)

Length scales of turbulence in stably stratified mixing layers. *Phys. Fluids*, **12**, 1327-1342, 2000. (W.D. Smyth and J.N. Moum).

Anisotropy of turbulence in stably stratified mixing layers. *Phys. Fluids*, **12**, 1343-1362, 2000. (W.D. Smyth and J.N. Moum).

The efficiency of mixing in turbulent patches: inferences from direct simulations and microstructure observations. *J. Phys. Oceanogr.* **31**, 1969 – 1992, 2001. (W.D. Smyth, J.N. Moum and D.R. Caldwell)

Waves and instability in an asymmetrically stratified jet, *Dyn. Atmos. Ocean*, 35, 265-294, 2002 (W.D. Smyth and J.N. Moum).

Differential diffusion in breaking Kelvin-Helmholtz billows, *J. Phys. Oceanogr.*, 35, 1004-1022, 2005. (W.D. Smyth, J.D. Nash and J.N. Moum)

Development of high-speed temperature measurements using thermocouples

The need for high-speed temperature measurements to supplant those made by traditional glass-bead thermistors arose for 2 reasons:

1. increased usage of airfoil (shear) probes which required faster flow rates than a thermistor could properly resolve;
2. rapidly-profiling turbulence instruments, such as our CHAMELEON, allowed more comprehensive observations at the expense of degraded temperature resolution.

In response to a community need for faster temperature measurement, we designed, developed tested and further used a thermocouple on both our vertically-profiling platform, CHAMELEON and our horizontally-profiling platform, MARLIN. Perhaps most importantly, though, we discovered through comparison that individual thermistors have unique frequency response transfer functions, that, when properly measured, can then be applied to obtain a nearly complete temperature spectrum, even at high flow speeds (> 1 m s^{-1}). This, in turn, led to our development (under NSF funding) of a moored mixing measurement, prototype presently deployed at 0°, 140°W.

A thermocouple probe for high speed temperature measurements in the ocean, *J. Oceanic Atmos. Technol.*, **16**, 1474-1482, 1999. (J.D. Nash, D.R. Caldwell, M.J. Zelman and J.N. Moum)

Differential diffusion

The measurement of salinity microstructure using a miniaturized 4-electrode conductivity sensor was evaluated based on measurements made in B.C. tidal channels and over Oregon's shelf. This led to the first estimates of salinity variance dissipation rate and an assessment of the feasibility of differential diffusion of heat and salt in the ocean, both from an observational and a theoretical/modeling view.

Estimating salinity variance dissipation rate from microstructure conductivity measurements, *J. Oceanic Atmos. Technol.*, **16**, 263–274, 1999. (J.D. Nash and J.N. Moum)

Microstructure observations of turbulent salinity flux and the dissipation spectrum of salinity. *J. Phys. Oceanogr.*, **32**, 2312-2333, 2002. (J.D. Nash and J.N. Moum).

Differential diffusion in breaking Kelvin-Helmholtz billows, *J. Phys. Oceanogr.*, 35, 1004-1022, 2005. (W.D. Smyth, J.D. Nash and J.N. Moum)

Hydraulically-controlled flows over the continental shelf

Our explorations of the continental shelf led to the discovery of the existence of high-drag states due to hydraulically-controlled flows. These represent form drag on the larger-scale circulation. It is thought that form drag represents 50% of the drag on the circulation in the lower atmosphere and the parameterization of this effect in atmospheric circulation models is considered critical to achieving a meaningful solution. However, form drag is NOT included in coastal circulation modeling efforts and its importance to coastal flows is unknown.

Topographically-induced drag and mixing at a small bank on the continental shelf. *J. Phys. Oceanogr.* , **30**, 2049-2054, 2000. (J.N. Moum and J.D. Nash).

Internal hydraulic flows on the continental shelf: high drag states over a small bank. *J. Geophys. Res.*, **106**(C3), 4593-4612, 2001. (J.D. Nash and J.N. Moum).

Nonlinear internal waves

Detailed observations of nonlinear internal waves, both surface-trapped waves of depression and bottom-trapped waves of elevation, have resulted in several new findings.

- turbulence generation by highly-strained density interfaces caused by the waves points out the importance of thinking in terms of a non-KdV framework, which does not produce such wave structure
- the existence of trapped wave cores was shown
- the signature of the pressure field of a wave was evaluated and its magnitude at the seafloor estimated – this is important in terms of determining the wave's interaction with the bottom and the in designing new forms of coastal soliton wave antennae
- the condition for wave release from a buoyant gravity current was clearly defined from observations.

Structure and generation of turbulence at interfaces strained by internal solitary waves propagating shoreward over the continental shelf, *J. Phys. Oceanogr.*, 33, 2093-2112, 2003. (J.N. Moum, D.M. Farmer, W.D. Smyth, L. Armi and S. Vagle).

Internal solitary waves of elevation advancing on a sloping shelf, *Geophys. Res. Lett.* **30**, OCE 3-1 – 3-4, 2003. (J. M. Klymak and J.N. Moum)

River plumes as a source of large-amplitude internal waves in the coastal ocean, *Nature*, 437, 400—403, doi:10.1038/nature03936, 2005. (J.D. Nash and J.N. Moum)

The pressure disturbance of a nonlinear internal wave train, in press, *J. Fluid Mech*, 2005. (J.N. Moum and W.D. Smyth)

Publications fully or partially supported by this grant:

1996 Efficiency of mixing in the main thermocline, *J. Geophys. Res.*, **101**, 12,057–12,069. (J.N. Moum)

Energy-containing scales of turbulence in the ocean thermocline, *J. Geophys. Res.*, **101**, 14,095–14,109. (J.N. Moum)

1997 Decay of turbulence in the upper ocean following sudden isolation from surface forcing, *J. Phys. Oceanogr.*, **27**, 810–822. (W.D. Smyth, P.O. Zavialov and J.N. Moum)

1998 Quantifying vertical fluxes from turbulence in the ocean, *Oceanography*, **10**, 111–115. (J.N. Moum)

Dynamic instability of stratified shear flow in the upper equatorial Pacific, *J. Geophys. Res.*, **103**, 10,323–10,338. (C. Sun, W.D. Smyth and J.N. Moum)

1999 Turbulent dissipation during a westerly wind burst: a comparison of large eddy simulation results and microstructure measurements. *J. Phys. Oceanogr.*, **29**, 1, 1–28. (E. Skyllingstad, W.D. Smyth, J.N. Moum and H. Wijesekera)

Estimating salinity variance dissipation rate from microstructure conductivity measurements, *J. Oceanic Atmos. Technol.*, **16**, 263–274 (J.D. Nash and J.N. Moum)

A thermocouple probe for high speed temperature measurements in the ocean, *J. Oceanic Atmos. Technol.*, **16**, 1474-1482. (J.D. Nash, D.R. Caldwell, M.J. Zelman and J.N. Moum)

2000 Topographically-induced drag and mixing at a small bank on the continental shelf. *J. Phys. Oceanogr.* , **30**, 2049-2054. (J.N. Moum and J.D. Nash).

Length scales of turbulence in stably stratified mixing layers. *Phys. Fluids*, **12**, 1327-1342. (W.D. Smyth and J.N. Moum).

Anisotropy of turbulence in stably stratified mixing layers. *Phys. Fluids*, **12**, 1343-1362. (W.D. Smyth and J.N. Moum).

2001 Internal hydraulic flows on the continental shelf: high drag states over a small bank. *J. Geophys. Res.*, **106**(C3), 4593-4612. (J.D. Nash and J.N. Moum).

The efficiency of mixing in turbulent patches: inferences from direct simulations and microstructure observations. *J. Phys. Oceanogr.* **31**, 1969 – 1992. (W.D. Smyth, J.N. Moum and D.R. Caldwell)

2002 Microstructure observations of turbulent salinity flux and the dissipation spectrum of salinity. *J. Phys. Oceanogr.*, **32**, 2312-2333. (J.D. Nash and J.N. Moum).

Waves and instability in an asymmetrically stratified jet, *Dyn. Atmos. Ocean*, 35, 265-294. (W.D. Smyth and J.N. Moum).

2003 Structure and generation of turbulence at interfaces strained by internal solitary waves propagating shoreward over the continental shelf, *J. Phys. Oceanogr.*, 33, 2093-2112. (J.N. Moum, D.M. Farmer, W.D. Smyth, L. Armi and S. Vagle).

Internal solitary waves of elevation advancing on a sloping shelf, *Geophys. Res. Lett.* **30**, OCE 3-1 – 3-4. (J. M. Klymak and J.N. Moum)

2004 Convectively-driven mixing in the bottom boundary layer, *J. Phys. Oceanogr.*, 34, 2189-2202. (J.N. Moum, A. Perlin, J.M. Klymak, M.D. Levine, T. Boyd and P.M. Kosro)

Form drag and mixing due to tidal flow past a sharp point, *J. Phys. Oceanogr* , 34, 1297-1312. (K. A. Edwards, P. MacCready, J.N. Moum, G. Pawlak, J. M. Klymak and A. Perlin).

2005 Differential diffusion in breaking Kelvin-Helmholtz billows, *J. Phys. Oceanogr.,* 35, 1004-1022. (W.D. Smyth, J.D. Nash and J.N. Moum)

The pressure disturbance of a nonlinear internal wave train, in press, *J. Fluid Mech.* (J.N. Moum and W.D. Smyth)

River plumes as a source of large-amplitude internal waves in the coastal ocean, *Nature*, 437, 400—403, doi:10.1038/nature03936 (J.D. Nash and J.N. Moum)

Book Chapters, Book Reviews

2001 Upper ocean mixing processes. *Encyclopedia of Ocean Sciences*, **6**, Academic Press, 3093-3100 (J.N. Moum and W.D. Smyth)

Three-dimensional turbulence. *Encyclopedia of Ocean Sciences*, **6**, Academic Press, 2947-2955 (W.D. Smyth and J.N. Moum)